CHAPTER 6

Methods for passive acoustic tracking of marine mammals: estimating calling rates, depths and detection probability for density estimation

Danielle CHOLEWIAK, Denise RISCH,
Robert VALTIERRA, and Sofie M. VAN PARIJS

1. Introduction

Anthropogenic activities and their impacts on marine ecosystems are steadily becoming an issue of global concern. From fisheries interactions to pollution, shipping and habitat degradation, human activities are driving ecosystem changes and are increasingly threatening the existence of numerous marine species (Davidson *et al*., 2012; Halpern *et al*., 2007; Kappel, 2005; Read, 2008). For scientists working within a management framework, effective and efficient means for assessing species distribution, abundance and their risk of impact by anthropogenic threats is of critical importance. Government agencies, such as the National Oceanic and Atmospheric Administration (NOAA) in the U.S., include within their mission the conservation, protection and recovery of marine species. This incorporates the evaluation of marine mammal abundance and occurrence, assessing the effects of sound on acoustic communication, hearing and behavior, monitoring interactions with fisheries, and evaluating the risk of vessel interactions (i.e. ship strikes).

Passive acoustic approaches for studying marine animal populations have expanded substantially in both depth and breadth over the past decade. Advances in hardware and software are now mature enough to allow data collection in remote areas as well as for species that are difficult to access using conventional approaches. More recently, new theoretical methodologies applied to acoustic data provide insightful ways of approaching large-scale ecological questions. These range from approaches that demonstrate the use of acoustic indices for monitoring biodiversity and species richness, to modeling (Clark *et al*., 2009) and measuring the effects of anthropogenic activities on marine animals. In this light, the use of passive acoustic methodologies to describe animal distribution, abundance and behavior are increasingly being recognized as a tool not only for basic research, but with clear applications for monitoring and mitigation to inform management and conservation strategies.

For management and research focused on cetaceans, surveys have traditionally been conducted visually, from either vessel or aerial platforms. However, it is recognized that these methodologies are affected by limitations in sighting conditions, particularly daylight and weather, as well as the amount of time the animals spend at the surface (i.e. 'sighting bias') (Clark *et al*., 2010). Recent passive acoustic studies have shown the extended occurrence and persistence of species beyond seasons and regions where they were previously documented through visual surveys (Morano *et al*., 2012; Mussoline *et al*., 2012; Vu *et al*., 2012). Therefore, it is becoming evident that whenever passive acoustic monitoring is applied to a region, the results show greater occurrence and persistence of species compared with visual survey data. These studies clearly demonstrate the fact that we are currently not collecting data in a way that fully describes the actual distribution, occurrence and abundance of marine mammals.

To enable managers and regulators to use passive acoustic monitoring effectively, either alone or in combination with visual surveys, several levels of acoustic information are needed. Characterization of species-specific call features in different contexts are necessary for baseline monitoring of seasonal and spatial species occurrence. Additionally, information on animal depth is important, as both the range over which vocalizations are detected, and the impacts to animals from anthropogenic activities may be heavily dependent on their location within the water column (Stafford *et al*., 2007; Thode, 2005; Vaage and Ursin, 1987).

Although still a young field, developments in statistical methodologies are enabling the incorporation of acoustic data into models to calculate animal density and abundance (Dawson and Efford, 2009; Efford *et al*., 2009). Marques *et al*. (2012) summarize the significant advances that are currently being made in the field of density estimation from passive acoustics. Their review highlights the essential need for baseline data on vocalization rates and group sizes in different behavioral contexts, by sex and age class, as well as the importance of collecting these data on different seasonal and spatial scales. These data are extremely scarce for most species. While the increasing availability of technologies such as digital recording tags has allowed for expanded studies that can provide information on individual calling rates, depth and underwater behavior (Baird *et al*., 2006; Oleson, Calambokidis, Burgess, *et al*., 2007; Parks *et al*., 2011; Wiley *et al*., 2011), the use of this technology is often constrained by cost, feasibility and effort needed to obtain adequate sample sizes. However, with the proliferation of fixed and towed hydrophone data, and new techniques for two- and three-dimensional localization and acoustic tracking, we have the opportunity to collect information that addresses these existing data gaps.

At NOAA's Northeast Fisheries Science Center, the Passive Acoustic Research Group is primarily working on collecting acoustic data in the western North Atlantic Ocean using a variety of fixed and mobile platforms. This work is focused on the acoustic ecology of marine mammals. We are part of a larger network of scientists conducting acoustic research throughout NOAA. Across the local, regional and federal government levels within the U.S., there is growing recognition that passive acoustic research is a vital component of future management strategies, however direct investment in research and infrastructure from NOAA is still lacking. Our work ties together long-term monitoring of marine species and mitigation of anthropogenic threats. Ultimately, our aim for these data is to improve broader marine management and conservation strategies.

In this chapter we present several pertinent approaches in analyses of passive acoustic data and discuss how they can improve our current modus operandi. We highlight two cases studies or 'applications', using data collected with both a towed array and bottom-mounted recorders. We demonstrate how these data can be used to address questions about animal abundance, behavior and occurrence. In turn, we discuss how this information can be applied to improving marine mammal management approaches for long-term occurrence, stock assessment and ship strike avoidance.

2. Application 1: Using acoustic arrays to create 2-D and 3-D tracks of North Atlantic right whales

Photo credit: Peter Duley / NOAA / NEFSC

Due to past exploitation and continuing pressure as a result of human-caused mortality, such as vessel strikes and entanglements, the North Atlantic right whale (*Eubalaena glacialis*) is one of the most critically endangered baleen whale species worldwide (Kraus *et al*., 2005). Although for the past two decades monitoring and management of this species have relied primarily on visual survey methodologies (Fujiwara and Caswell, 2001; Kraus, 1990) in recent years advances in technology and analysis tools have resulted in a wider appreciation of the use of passive acoustic monitoring (PAM) to augment traditional visual surveys and management frameworks (Van Parijs *et al*., 2009).

Several studies have investigated the vocal behavior of North Atlantic right whales (Mellinger, 2004; Morano *et al*., 2012; Mussoline *et al*., 2012; Vanderlaan *et al*., 2003). The two main call types produced by this species are 'up-calls', which are believed to serve as social contact calls and 'gunshot sounds', used in reproductive advertisement (Parks and Tyack, 2005; Parks *et al*., 2005). A few studies have started to investigate individual right whale vocal behavior to assess acoustic parameters such as calling rate, depth, temporal trends in vocalizations, as well as the frequency of occurrence of different call types. These data have been collected in short-term behavioral studies using a combination of dedicated focal follow approaches and the use of new technologies such as short-term recording tags (Matthews *et al*., 2001; Parks *et al*., 2011b). However, these approaches are generally both costly as well as limited in terms of sample size.

Since vocal behavior can be highly variable as a function of behavioral state, sex and age-class, and can vary by season and region (Van Parijs *et al*., 2009; Parks and Tyack, 2005; Parks *et al*., 2005), it is essential to collect data on right whale acoustic behavior on larger spatial and temporal scales, as well as across more individuals in order to better understand the detectability of right whales for passive acoustic monitoring applications. Longer term data sets collected with passive acoustic arrays and new analysis tools for detection and localization could help to start fill these gaps (Parks *et al*., 2012a). In addition, these data can provide valuable baseline information in relation to ship-strike management and mitigation of other anthropogenic impacts such as noise (Parks *et al*., 2011a, 2012b).

In this case study, we use a one-hour time series of PAM data and apply the 2-D localization method used by Parks *et al*. (2012), to demonstrate its feasibility for analyzing tracks of vocalizing right whales, as well as determine calling rates and other parameters of right whale calling behavior. In addition, we also provide background demonstrating a new method for 3-D localization and apply this technique for depth estimation of calling right whales using a single recording unit.

2.1 Methods

2.1.1 Data collection

Acoustic recordings of North Atlantic right whales were collected using an array of ten bottom-mounted archival recording units (MARUs) (Calupca *et al*., 2000). The array used for this application was placed in the southwest corner of the Stellwagen Bank National Marine Sanctuary (SBNMS) from March 28th to May 27th 2009 (fig. 1). This array forms part of a longer term near continuous data collection effort from 2006 to 2011 throughout SBNMS. For this effort, ten MARUs were placed for 3 month periods in areas with high baleen whale densities (see http://www.nefsc.noaa.gov/psb/acoustics/psbAcousticDeployments.html). SBNMS and Cape Cod Bay are well-known spring feeding habitats for North Atlantic right whales (Mussoline *et al*., 2012; Pendleton *et al*., 2012). Individual MARUs were spaced 3 nautical miles apart and placed in depths ranging from 28 to 82 m. The HTI-94-SSQ hydrophone of each MARU had a sensitivity of -168 dB re 1 V/µPa and was connected to a 23.5 dB preamplifier. The frequency response was flat (±1 dB) over the 10-585 Hz frequency range. MARUs were programmed to record continuously at a sampling rate of 2000 Hz with 12-bit resolution.

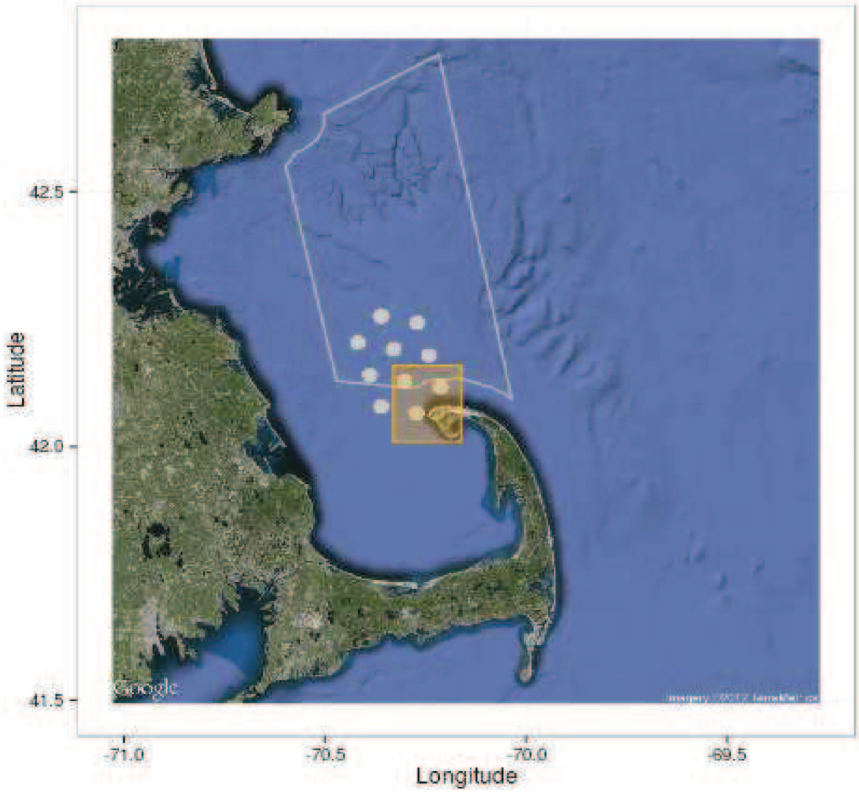


Figure 1: Map of the study region, north of Cape Cod, MA, USA. The white line indicates the Stellwagen Bank National Marine Sanctuary (SBNMS). Dots represent locations of marine autonomous recordings units (MARUs) and the yellow shaded area indicates the subarea plotted in Figure 6.

2.1.2 Two-Dimensional Tracking

For this study, the MARU recordings from the array mentioned above were time-synchronized and compiled into 10-channel data files. The Matlab-based (2010a, The MathWorks, Natick, MA, USA) sound analysis software XBAT (Figueroa and Robbins, 2008) was used for acoustic analysis and spectrogram generation (Hanning window, 1024 pt FFT). Right whale up-calls were detected by visual inspection of spectrograms and listening to sound files. One hour of data was selected for detailed analysis. Selection was based on review of the signal arrival patterns indicating the presence of clear, locatable right whale up-calls (Parks and Tyack, 2005), as well as the close proximity of several vocally active individuals to at least one recording unit. Three individual right whales were tracked for this analysis.

A two-dimensional (x, y) position was computed for each selection using the correlation sum location estimation (CSE) tool developed for XBAT (Cortopassi and Fristrup, 2005). The CSE algorithm calculates the sum of waveform cross-correlation values across all selected channel pairs for a grid of spatial points. The candidate location at which these values are maximized is selected as the most likely location. This method appears to be more robust to background noise than traditional localization methods that are based on hyperbolic fixing and rely on correlation peak picking. Each location was reviewed to ensure that the correct call was selected on all channels and that the estimated location agreed with observed arrival patterns across channels. Incorrect selections or location estimates were eliminated from the localization dataset.

A calibration experiment was conducted to empirically determine the localization error with this array configuration. 47 frequency-modulated tones were played at five known locations and depths within the array. Locations of these events were estimated using the CSE tool and location error in meters was calculated by subtracting the estimated position from the known location of the underwater speaker during transmission. Mean localization error was about 53.2 m (sd 30.8). To reduce the impact of localization error between calls, estimated tracks were smoothed using a moving average (MA) technique. The smoothed location at a specific point in time was calculated by averaging the surrounding five location estimates (Hen *et al*., 2004).

2.1.3 Calling rates

Calling rates were calculated for all three tracked right whales over the hour of analysis. Bouts of calling were separated using the bout criterion interval (BCI), as determined by plotting inter-call intervals (ICIs) on a logarithmic scale (Parks *et al*., 2011b; Slater and Lester, 1981). Mean and standard deviation for ICIs within bouts and inter-bout intervals (IBIs) were estimated based on the BCI.

2.1.4 Three-dimensional tracking and calling depths

Right whale calling depths were estimated with the multipath localization technique Direct-Reflected Time Difference of Arrival (DRTD). This method uses the direct path of an acoustic signal along with a varying combination of surface and/or bottom reflections (referred to multipath 'orders') of the signal to localize an animal (fig. 2). This method can be applied to multiple MARUs to resolve a three-dimensional source location, or to a single unit to resolve a two-dimensional (depth and radius) solution. In the case where MARUs are widely spaced, full three-dimensional localization with DRTD will not likely be possible due to radial limitations (see Results section below). However, three-dimensional localization can still be resolved when using DRTD as a supplement to TDOA, by applying TDOA to resolve 'in-plane' (x, y) localization, and DRTD for depth estimation. Solutions for the two methods can also be verified through comparison of the two estimated radial distances (using TDOA and DRTD) from the MARU channel to verify agreement.

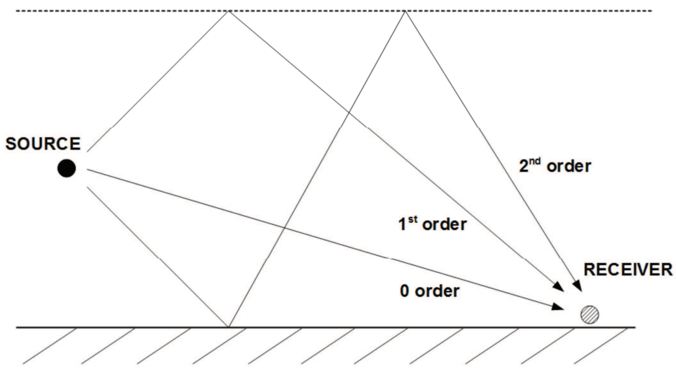
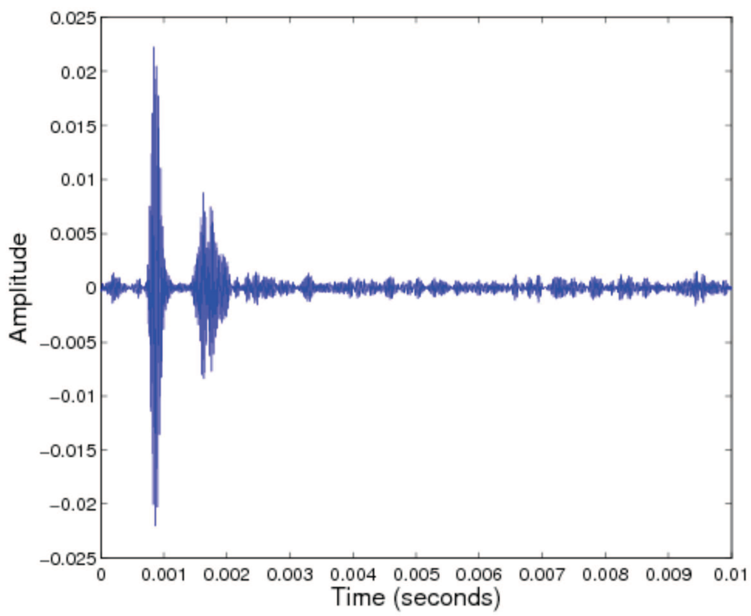


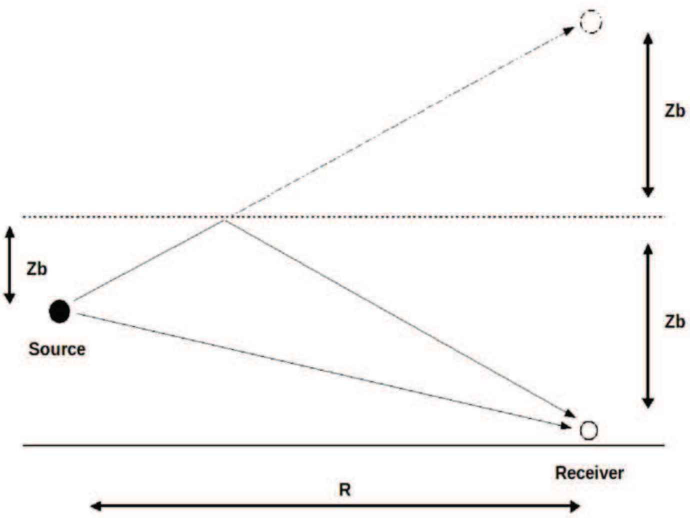
Figure 2: A diagram illustrating the multipath sound propagation from a source to the receiver (a bottom-mounted MARU).

2.1.4.1 Brief Background of the DRTD methodology

DRTD is a ray-based localization method, meaning that all signal paths are assumed to be straight line paths with the direction only changing as a result of either ocean surface or bottom reflections. Any effects due to sound stratification have been assumed to be negligible due to the relatively short path lengths and shallow depths of the sound channel in which the MARUs were placed. With DTRD, the time difference of arrival between the initially received 'direct-arrival' and a reflection of the signal are used to calculate the difference in path length between the two signals (fig. 3). By knowing the depth of the MARU and the time difference of arrival between the direct and reflected signal, a series of possible solutions for the source depth and radial distance from the MARU may be calculated.



(a)



(b)

Figure 3: (a) A time series with a pulsed signal and it's multipath surface reflection with a direct-reflected time difference of approximately 1ms. (b) Application of Lloyd's mirror to determine path lengths.

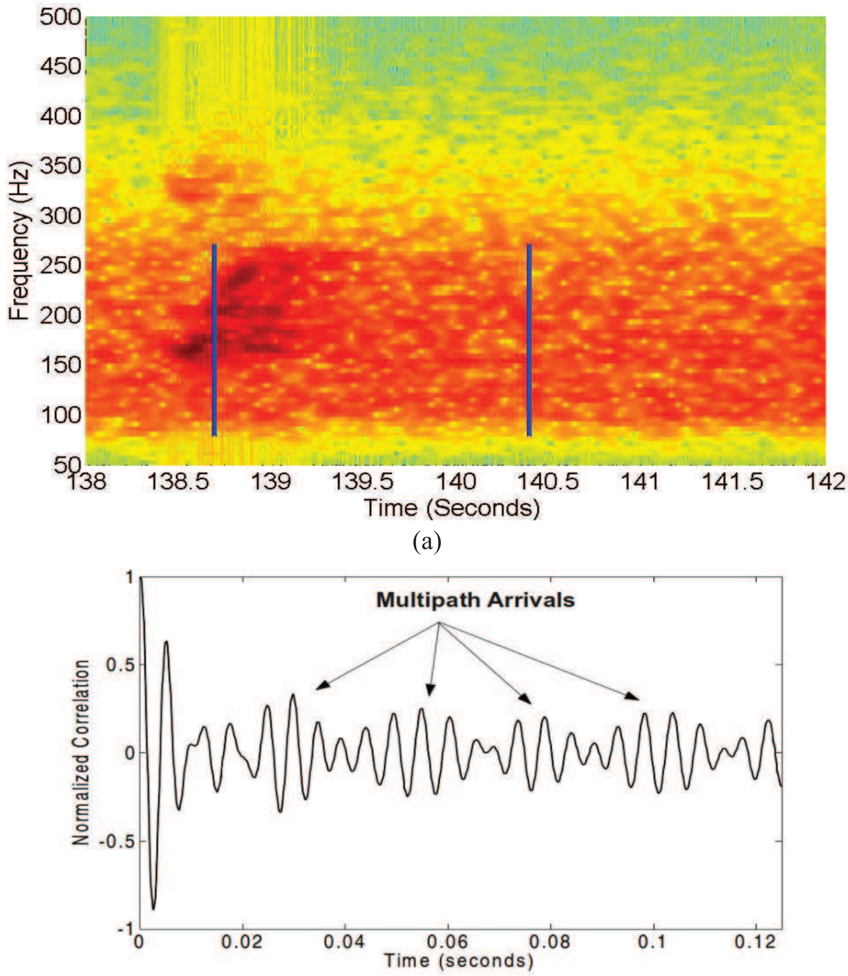
2.1.4.2 Application of the Autocorrelation method

Multipath time differences can vary from fractions of a millisecond to hundreds of milliseconds or more. Based on the depths of our study area (<100 m), measured time differences will be at most tens of milliseconds. Therefore, this creates a problem when attempting to apply standard multipath localization to a right whale: given signal periods of approximately one second for up-calls and the short time differences between multipath arrivals, overlap in the signals will make the task of distinguishing them very difficult.

This problem may be addressed through the application of an autocorrelation method, which takes advantage of the assumption that reflected signals are images of the direct signal and that the frequency is changing with time (like a reflected up-call)(Valtierra *et. al*., 2013). Using this method, knowledge of amplitude and phase is arbitrary and only the time-series of the direct-reflected signal is necessary for analysis. When the target signal is cross-correlated with itself, the time delay between multipath arrivals will be indicated by a series of local correlation peaks. The process is as follows: initially, an up-call is selected and windowed for autocorrelation (fig. 4a). The window is selected to include the most 'linear' part of the signal while leaving 'buffer' space beyond the signal. An autocorrelation is applied, and the time lag at which each correlation peak occurs corresponds to the time difference of arrival between the direct and reflected signal arrivals (fig. 4b).

2.1.4.3 Application of the forward method

In the application of DRTD, there are two unknowns: depth and radius. For a single direct-reflected time difference, there are several depth and radius combinations for the source that will result in the same time difference of arrival. This ambiguity can be overcome when there are several multipaths. By resolving several time differences between the direct arrival and a number of multipaths, several solution sets for depth and radius may be calculated, and successful localization is achieved if the solution sets converge at one unique point. This method can be called the 'forward method' because it directly uses the time difference measurements to calculate a set of location solutions. However, this method can be computationally intensive especially when using more than two solution sets for localization. A simpler approach may be taken through application of the 'backward method' coupled with a probability surface.



(b)

Figure 4: (a) A spectrogram of a windowed right whale up-call for autocorrelation analysis. FFT: 512 pts, bandpass filter 100-250 Hz. (b) Autocorrelation results of the up-call showing peaks corresponding to multipath arrivals.

2.1.4.4 Application of the backward method and probability surfaces

Unlike the forward method, where measured time differences are used to calculate a solution set of possible depth and radius pairs, the backward method considers every possible depth and radius within a defined space and resolution. This essentially works by the creation of a two-dimensional grid containing discrete points that correspond to possible source depths and radial distances. The simplicity lies in the comparison of the processed solution sets; where the forward method requires a multi-step algorithm capable of quickly sifting through multiple solution sets looking for a convergence point is computationally intensive, the backward method only requires the summation of probability surfaces and finding the point of highest probability of solution convergence.

In defining a solution space, the maximum depth may be determined by the depth of the recorder, and the radial distance and grid point spacings are determined by the practical limits relative to the minimum resolvable TDOA (see results below). The direct and multipath distances of each order to the MARU for all grid points may be calculated allowing for the time difference of arrival to be resolved by taking the difference in path lengths divided by the speed of sound. These results in a specific time difference of arrival assigned to each grid point for each multipath order. Using the geometric method, equations for the path lengths may be derived.

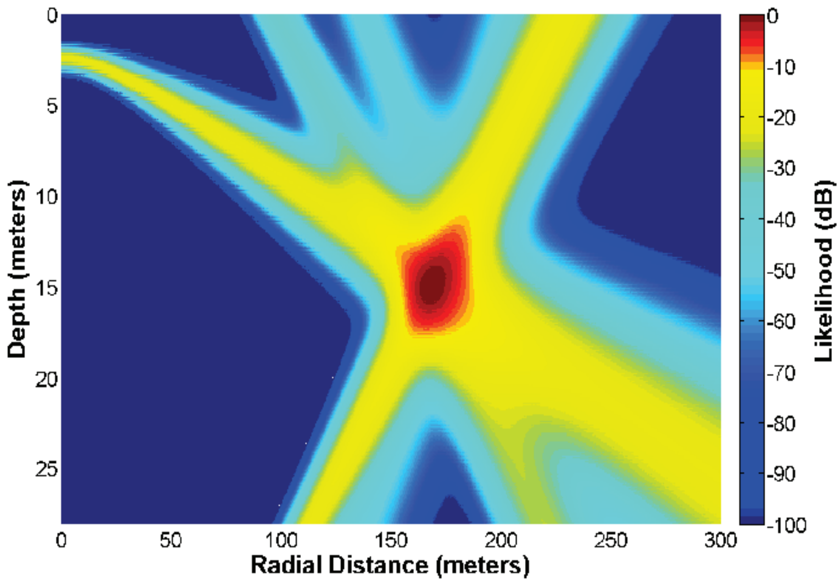


Figure 5: The sum of probability surfaces leads to a convergence at a unique point. This example is taken from the 2-D localization of a synthetic signal transmitted during an empirical calibration experiment. Radial distance refers to the distance from the MARU. (Valtierra *et al*., in press)

After calculating the corresponding multipath time difference for each grid point, a probability surface may then be created by applying the probability density function (PDF) to each grid point. The PDF is assumed to have normal Gaussian distribution centered at the mean, or best estimate dte_n and standard deviation σ_n. The best estimate is the actual multipath TDOA measured through analysis of signal data recorded by the MARU. Using dte_n and σ_n, the PDF is then iterated over the entire grid using the time difference at each grid point to create a likelihood surface for each multipath order. The resulting likelihood surfaces contain areas of high probability corresponding to grid points where the calculated TDOA is close to the actual TDOA measured in the received acoustic signal (dte_n). The remaining outlying points had a low probability. The likelihood surfaces for every available multipath order are then summed together. Successful localization is achieved when the summed probabilities for all orders converge into a unique area of high likelihood (fig. 5).

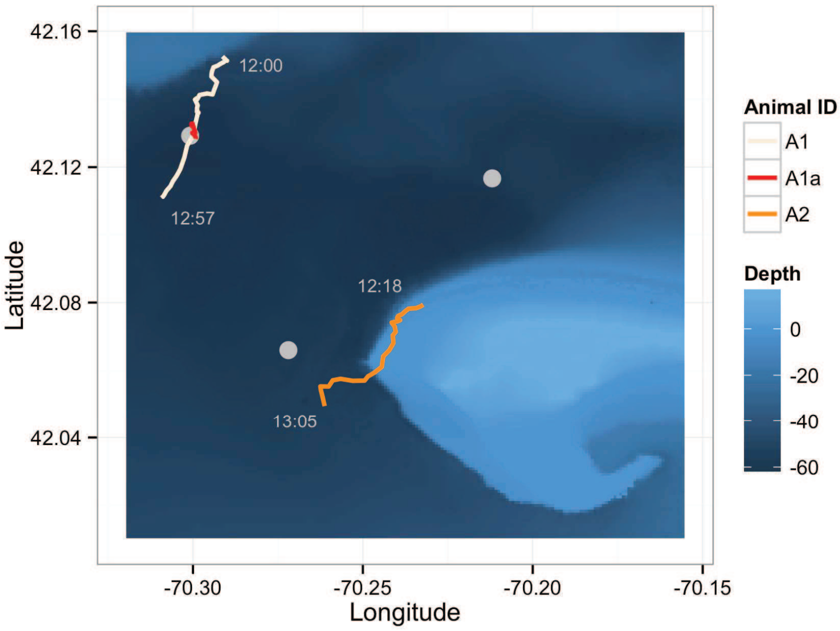


Figure 6: This figure represents a detailed map of the yellow shaded area in Figure 1. The figure shows the smoothed tracks of three North Atlantic right whales tracked using their up-calls during the one hour of analysis. Dots represent the MARUs used for localization and the lines represent tracks of calling animals, colored by Animal ID in the figure legend

2.2 Results and discussion

2.2.1 Two-Dimensional Tracking and Calling Rates

A total of 108 right whale up-calls made by three individual right whales were localized during the one hour time period (fig. 6). Over this period, calling rates averaged approximately one call per minute with inter-call intervals of 30 seconds (tab. 1). The bout criterion interval (BCI) determined from this analysis was 100 seconds and agreed with previously published values (Parks and Tyack, 2005; Parks *et al*., 2011b). Inter-bout intervals were approximately four minutes on average (tab 1).

Table 1: Estimates of North Atlantic right whale up-calling rates for each of the acoustically tracked individual whales (A1,A1a,A2) observed during the one hour analysis. ICI: inter-call interval (time between start times of successive calls from one individual within a calling bout); IBI: inter-bout interval (time between bouts of calling, defined by a bout criterion interval (BCI) of 100 s based on inspection of the log-survivorship curve of ICIs.

Animal ID	N calls	Track dur. (min)	Call rate (calls/min)	Mean ICI (s)	±SD ICI (s)	Mean IBI (min)	±SD IBI (min)
A1	62	60	1.0	18.7	20.8	4.3	2.5
A1a	19	20	1.4	22.9	27.4	4.0	1.9
A2	27	45	0.4	54.2	21.9	4.9	2.2
Mean ±SD	**36 ±22.9**	**41.7 ±20.2**	**0.9 ±0.4**	**31.9 ±19.4**	**23.4 ±3.5**	**4.4 ±0.5**	**2.2 ±0.3**

2.2.2 Three-Dimensional Tracking and Calling Depths

Calling depths were estimated using the DRTD method and data from one bottom-mounted MARU for one of the three tracked right whales of the presented case study. The radial distance between right whale A1a and the closest MARU ranged from 100 to 500 m (fig. 6). Using 10 of 19 available calls, depth estimates for this individual whale ranged from 21 to 40 meters (fig. 7).

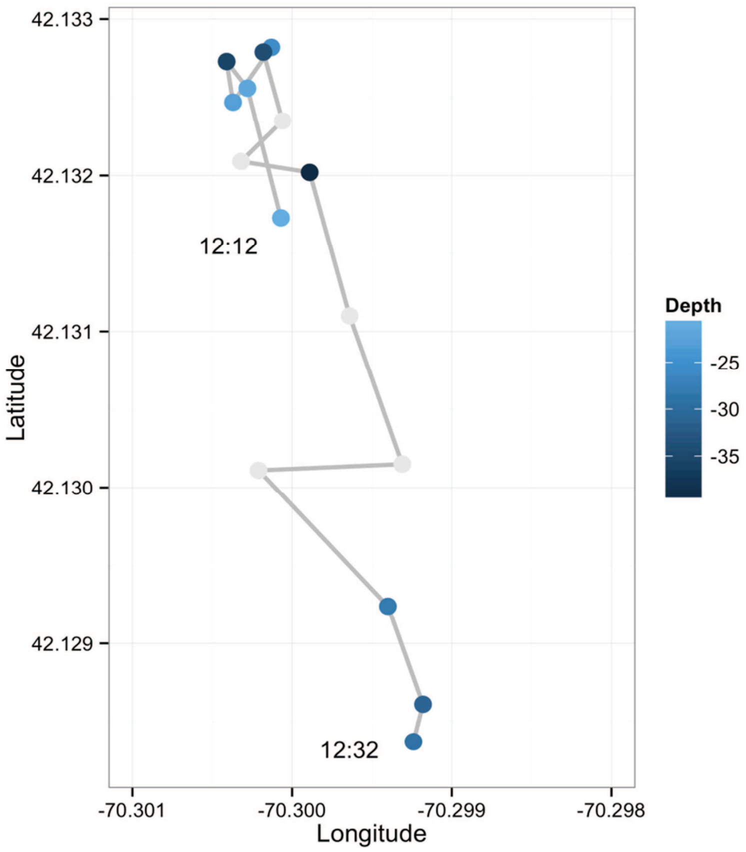


Figure 7: Detailed map of tracked North Atlantic right whale A1a, showing calling depth for calls that could be located using the DRTD method.

2.2.3 Limits to DRTD: Prediction of minimum time difference and maximum resolvable radial distance

The ability to apply DRTD to baleen whale vocalizations is inherently limited by the ability to resolve multipath arrivals in the acoustic signal, which is dependent on both source and recorder depth. As the sound source moves farther from the MARU or to very shallow depths, the direct reflected time difference of arrival decreases, and at a certain point the autocorrelation peaks overlap, making individual arrivals difficult to distinguish. This problem has the greatest effect on resolving the first order direct-reflected time difference and has the greatest impact on limiting the range over which this method may be applied. Predicting the minimum resolvable time difference between the direct and reflected signal arrivals can be used to estimate this limit.

The prediction may be made using a model for the autocorrelation solution of a right whale up-call (Valtierra *et al*., in press). An equation was derived to predict the minimum time difference using call parameters (call length and sweep rate) typical for the animal of interest resulting in the following relationship of $dt_{min} = \pi/(2\beta T)$ where β is the up-call sweep rate (Hz/sec) and T is the call length. Using this method and the mean values for a right whale up-call of $T = 0.99$s and $\beta = 111$Hz/s (Parks and Tyack, 2005), the minimum time difference that can be resolved between the direct and reflected call was found to be 14.3 ms.

Based on the minimum resolvable time difference and the path length geometry, the maximum range under which DRTD may be applied to right whale up-calls may be calculated. Because the time difference of arrival is a function of both calling depth and radius, this maximum range will vary.

The relationship between depth and radius for the current case study is plotted in fig. 8, based on a bottom-mounted MARU depth of 100 m, a sound speed of 1480 m/s, and a time difference of arrival of 14.3 ms. As can be seen from the plot, as the source increases in depth, the maximum radius quickly increases due to the specific geometric nature of the multipaths.

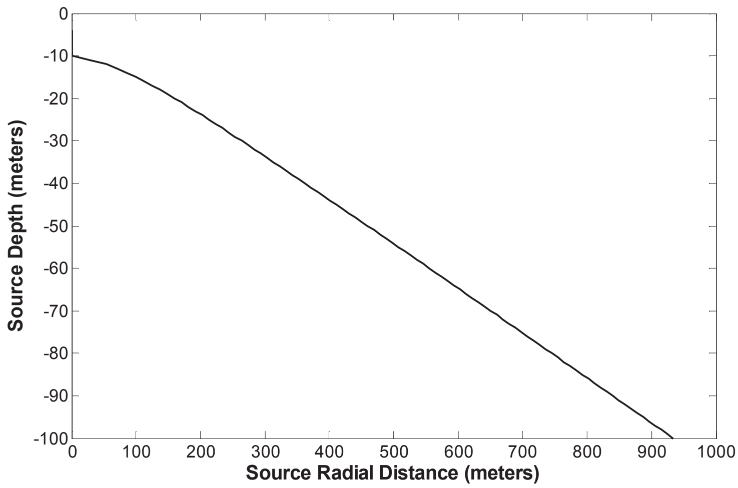


Figure 8: The depth relation for a first order direct-reflected time difference of 14.3 ms, assuming a bottom mounted MARU at a depth of 100 m with a sound speed of 1480 m/s.

Thus, in very shallow water, the application of the DRTD method is most likely impractical unless the source is very close to the MARU. For moderate source depths (greater than 100m) however, this method can localize animals at radial distances approaching one kilometer. Given the scale over which individual units in a fixed array may be placed, this method may be more practical as a supplement rather than a replacement to TDOA. However, when an animal is localized to within the range of DRTD, it is possible to obtain calling depth, using only one MARU. Given the large amounts of available PAM data sets, this method has the potential to significantly increase currently available data on calling depths for right whales and other baleen whale species. Moreover this information can be obtained without the need for improved equipment, and further the method is compatible with currently available and historic data sets.

3. Application 2: Using towed hydrophone arrays for 2-D and 3-D localization of beaked whales

Photo credit: NOAA/NEFSC

Beaked whales are notoriously difficult to detect via visual surveys, due to the fact that they spend long periods of time under water and tend to be relatively inconspicuous when at the surface. Visual detections of beaked whales during broad-scale cetacean surveys may decrease by an order of magnitude as sea state conditions change from Beaufort 1 to Beaufort 5

(Barlow *et al*., 2006), and less than 50% of individuals of some species are detected visually even under excellent sighting conditions (Barlow, 1999). Incorporating passive acoustic methodologies into visual surveys is therefore of critical importance for improving detections of these challenging species.

Little was previously known about the life history and social dynamics of most beaked whale species. However, research over the last decade has started to provide information about the characteristics of the vocalizations for many species. Visual encounters using boat-based surveys, short-term digital recording tags (DTAGs; (Johnson and Tyack, 2003)) (Dawson and Ljungblad, 1998; Gillespie *et al*., 2009; Hooker and Whitehead, 2002; Johnson *et al*., 2004; Rankin and Barlow, 2007; Rankin *et al*., 2011; Zimmer *et al*., 2005), and bottom-mounted recorders (Baumann-Pickering *et al*., 2010, 2012; McDonald *et al*., 2009), have enabled the description of species-specific vocalizations for over ten species. In addition, vocalizations of several species have been recorded from live- stranded or captive animals (Caldwell and Caldwell, 1991; Lynn and Reiss, 1992; Marten, 2000). Taken together, these data are beginning to form a solid foundation for incorporating passive acoustics into the methodologies used to detect and estimate the abundance of beaked whales.
Recently, intensive efforts centered on the occurrence of Blainville's beaked whales (*Mesoplodon densirostris*) in the Bahamas have helped to develop methodologies for density estimation using a combination of visual sightings, dense numbers of bottom-mounted hydrophones on a naval training range and DTAGs (Küsel *et al*., 2011; Marques *et al*., 2009; Moretti *et al*., 2010). However, for most researchers these extensive data acquisition methods are neither available nor practicable. To facilitate the evaluation of density and abundance of beaked whales on a broad scale, methodological approaches need to be married with other more standard data collection mechanisms, including incorporating acoustic data into traditional line-transect surveys.

Marques *et al*. (2012) describe a number of variables that need to be well-defined in order to incorporate acoustic data into density estimation frameworks. These include cue rate, the probability of detection, and detection distance. In the traditional line-transect framework, the observed distribution of sighting distances to animals or groups of animals is modeled to develop a detection function and determine the area for the survey (Buckland *et al*., 2001). For deep-diving animals, however, this presents a complication as the two-dimensional localization obtained through usual means (time difference of arrival or target-motion analysis) actually represents a slant distance to the vocalizing animal, not a perpendicular distance. Errors in measuring the distance to animals will affect the shape and precision of the detection function, which may lead to biases in the resulting abundance estimates or confidence intervals that are too narrow (Borchers *et al*., 2010).

To date this issue has been addressed in only one study on sperm whales (Barlow and Taylor, 2005a). In this case, the depth of the animals was found to have negligible impact on the overall density estimates, as the range of detection (on the order of several to many kilometers) was much greater than the modeled hypothetical depth of 500 m. For beaked whales, however, overall detection ranges are much shorter. For Cuvier's beaked whales, Zimmer *et al*. (2008) found that probably of detection was highest at distances of 700 m or less, with a maximum range of 4 km. For these species, the effect of the animal's depth may therefore have a relatively greater impact on error in 2-D range estimation. For example, consider an animal for which standard two-dimensional acoustic localization provides a (slant) distance of 300 m. If this animal is vocalizing at a depth of 200 m, the actual perpendicular distance to that individual would be 224 m, or 25% less than estimated by 2-D methods alone. Several species of beaked whales are thought to only produce sounds during deep (>200m) foraging dives (Tyack *et al*., 2006), and Yack *et al*. (2011) noted that most bearings obtained during a towed-array survey likely represented slant distances for animals at depth.

For most species we do not yet have the relevant data to assess the depths at which animals are vocally active, but increased application of three-dimensional localization methodologies can be used to address this issue. Several techniques have been established in previous studies, ranging from using more well-known methods like TDOA (Giraudet and Glotin, 2006) to methods which take advantage of multipath signal arrivals such as Direct Reflected Time Difference of Arrival (DRTD; (Nosal and Frazer, 2006; Thode, 2005)). Additionally, DRTD has also been applied to single hydrophone data to resolve depth and radius information even though latitude and longitude information may not be available (Aubauer *et al*., 2000; Mouy *et al*., 2012). In cases where multipath information is not available, modal or "group velocity" methods have been shown to provide a rough estimate for calling depths (Munger *et al*., 2011; Wiggins *et al*., 2004).

Currently, most efforts to estimate the abundance of beaked whales have primarily taken place only during cetacean surveys that were focused on other species (Barlow *et al*., 2006). Because individual species identification is challenging, these abundance estimates often lump several beaked whale species together (Waring *et al*., 2009). However, dedicated surveys in areas of known occurrence such as the Southern California Bight have demonstrated that the incorporation of acoustic methodologies for specific species can significantly improve upon detection rates using conventional visual observations (Yack *et al*., 2011). These results highlight the importance of increasing coordinated visual and acoustic efforts on abundance surveys.

In this application, we utilize data collected on a recent NOAA cetacean line-transect survey to demonstrate the application of analysis techniques for beaked whales. This survey enabled the characterization of the echolocation characteristics of Sowerby's beaked whales (*Mesoplodon bidens*) and improved the application of automated detectors to facilitate two-dimensional tracking. Here, we add to the single species approach discussed above and demonstrate the application of three-dimensional localization techniques to quantify the depths at which several animals were vocalizing.

3.1 Methods

3.1.1 Data Collection

In 2011, one half of the Atlantic Marine Assessment Program for Protected Species (AMAPPS) survey was conducted from the NOAA R/V Bigelow, throughout the western North Atlantic covering approximately 36°N to 42°N (fig. 9). Visual observations and acoustic recordings were collected simultaneously. Information on acoustic detections was not transmitted to visual observers in real-time. Visual sighting data were collected during daylight hours from approximately 06:00-18:00 EDT when sea conditions were less than sea state Beaufort 6, by two teams of trained observers operating from two different decks of the ship. In each team, two observers utilized high-powered "big-eye" binoculars (Fujinon, 25x150) to scan from the bow of the ship to 90° port or starboard, while one observer scanned the track line using hand-held binoculars and naked eye.

Acoustic recordings were collected using a three-element oil-filled hydrophone array (Benthos AQ-4 elements: -201dBV re: 1µPa), towed 300 m behind the ship, at approximately 12 m depth. Acoustic data were routed to a desktop computer via a Magrec HP/27ST monitor box (http://ecologicuk.co.uk, 80 Hz high-pass filter, 30 dB gain) and an external Fireface 400 sound card, with data recorded continuously at a sampling rate of 192 kHz utilizing the software package Pamguard (http://www.pamguard.org). Two-channel data were also routed to a second set of computers via an internal M-Audio soundcard, sampling at 44 kHz, for real-time detection and tracking of vocal animals utilizing the software packages WhalTrak and Ishmael. Survey speed averaged 10 knots.

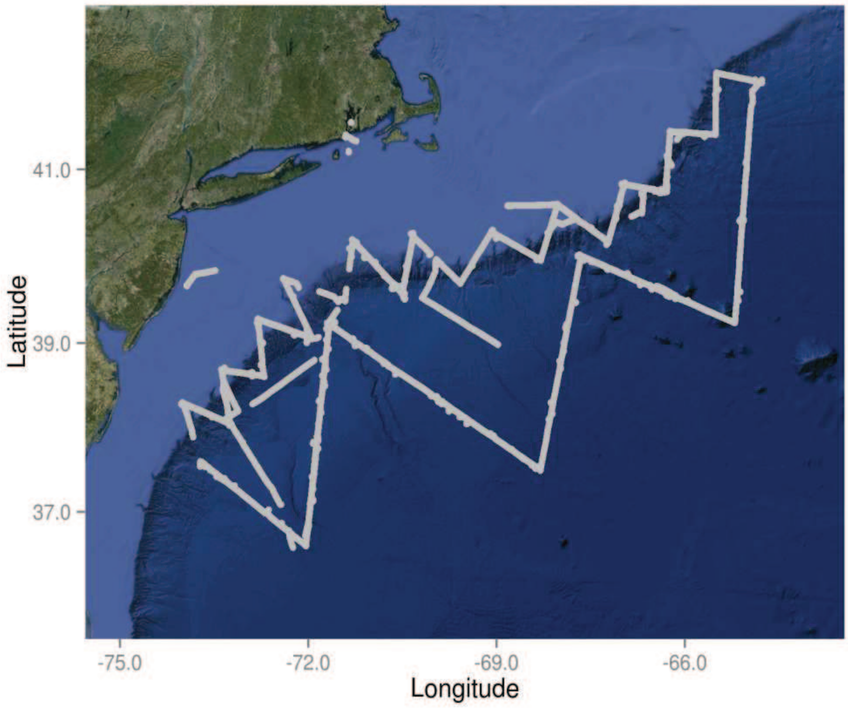


Figure 9: Area surveyed during the Atlantic Marine Assessment Program for Protected Species during the summer of 2011. Gray lines represent the actual vessel tracklines.

3.1.2 Acoustic analyses

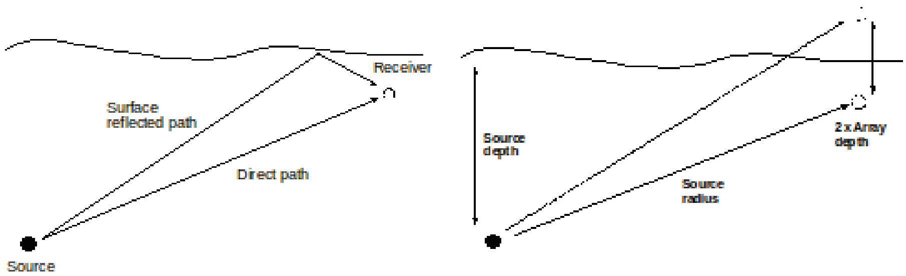
Acoustic data were post-processed using the software packages Raven (Charif *et al*., 2004) and Pamguard (Gillespie, 2008), as well as custom-written Matlab scripts. Data analyses took place in three stages: 1) identification and characterization of echolocation clicks, 2) development and application of automated click detectors, 3) two-dimensional and three-dimensional localization of individual click trains. The first stage of data analysis was previously described (Cholewiak *et al*., submitted). The second and third stages are described below.

3.1.3 Automated click detectors

The Pamguard software allows for the application and customization of an algorithm for the detection of transient acoustic signals, such as echolocation clicks. For the general detection of clicks, the user defines a set of parameters, including the signal threshold, the minimum number of samples between clicks, and the maximum length of clicks. By defining an additional set of criteria specific to the target signal, an automated classifier can be defined and applied as well. These additional criteria may include the signal's primary energy band, the peak and mean frequency, and the number of zero crossing.

3.1.4 Two-dimensional and three-dimensional localization

Pamguard Beta v1.11.02 currently allows for the application of target-motion analysis to compute two-dimensional locations of calling animals, using one of several algorithms (Gillespie *et al.*, 2008). This method is capable of resolving the relative bearing and radial distance of a given sound source at a specific moment in time. At any instant in time, the relative bearing of the source relative to the array can be calculated using a pair of hydrophones. Over multiple vocalizations (e.g. echolocation clicks in a click train), changes in the bearing of the source relative to the array result in a set of intersecting bearing lines which correspond to the target location (Barlow and Taylor, 2005a; Gillespie, 1997). This methodology makes the assumption that the source is stationary relative to the vessel, which is reasonable in many cases given that survey speeds are often faster than the speed at which animals are traveling. However, given that the radial distance is independent of the source depth relative to the array, this method only provides a means for two-dimensional localization.



(a) (b)

Figure 10: (a) The direct and reflected signal path from the source to array (b) A multipath model using virtual receiver to estimate the bearing of a multipath signal

Full three-dimensional localization can be accomplished by combining two techniques, intersecting bearing estimates and multipath signal arrivals, in a manner similar to work previously conducted on sperm whale surveys (Barlow and Taylor, 2005a; Gillespie, 1997; Thode, 2005). In general, this is accomplished by finding the time difference between the direct signal arrival and surface reflections to the array (fig. 10a). By treating the surface reflection like a signal traveling to a 'virtual receiver', an additional bearing estimate may be made, resulting in a vertical bearing (fig. 10b). Knowing the additional vertical bearing along with the radial distance of the source, the depth of the source can then be resolved. Custom Matlab scripts were used to perform both time-series and autocorrelation analysis to measure the direct and surface reflected time difference of arrival. The time difference of arrival was then used to calculate the vertical bearing relative to the array, allowing for the source depth estimation using basic trigonometry. This can be accomplished through application of bearing estimation in a manner similar to that of array applications, however in this application rather than estimating a bearing based on a time difference of arrival between two hydrophones, the time difference is between a single hydrophone and the “virtual receiver” illustrated in fig. 10b. In this application, the time difference dt is the direct reflected time difference of arrival, and the distance between hydrophones, is two times the array depth. Knowing the bearing angle the source depth may then be calculated with the target radius originally estimated using target motion analysis being treated as the hypotenuse of a triangle, and the remaining triangle sides being the horizontal distance and depth.

3.2 Results and discussion

On 4 July 2011, at approximately 07:40 EDT, the R/V Bigelow encountered several small groups of Sowerby’s beaked whales at 40.78˚N, 60.6˚W, just off the continental shelf of the eastern United States, near Georges Bank. Over a period of approximately 25 minutes, at least three groups of animals were sighted, including a singleton, a pair, and a group of four individuals. The groups were distributed over several kilometers. As the ship passed through the area, several animals crossed the survey track line, and were approximately 300 m distant at their closest point of approach. Simultaneous with this encounter, multiple series of high-frequency echolocation clicks were detected by the acoustic team. Thirty minutes of continuous acoustic data encompassing and following the period of the visual encounter were included in subsequent analyses.

Analyses of echolocation characteristics from over 4000 clicks revealed that the majority of clicks had a median peak frequency of 33 kHz, with a -3dB bandwidth of 6 kHz, and an inter-click interval of 96 ms (Cholewiak *et al*. submitted, fig. 11). In Pamguard, an automated click detector was subsequently applied to the acoustic data. The classification algorithm with frequency sweep was customized to identify clicks containing greater energy in a test band (30 – 37 kHz), compared to two control bands (15 – 18 kHz and 85 – 95 kHz), and to identify clicks containing a peak frequency between 29 – 37 kHz.

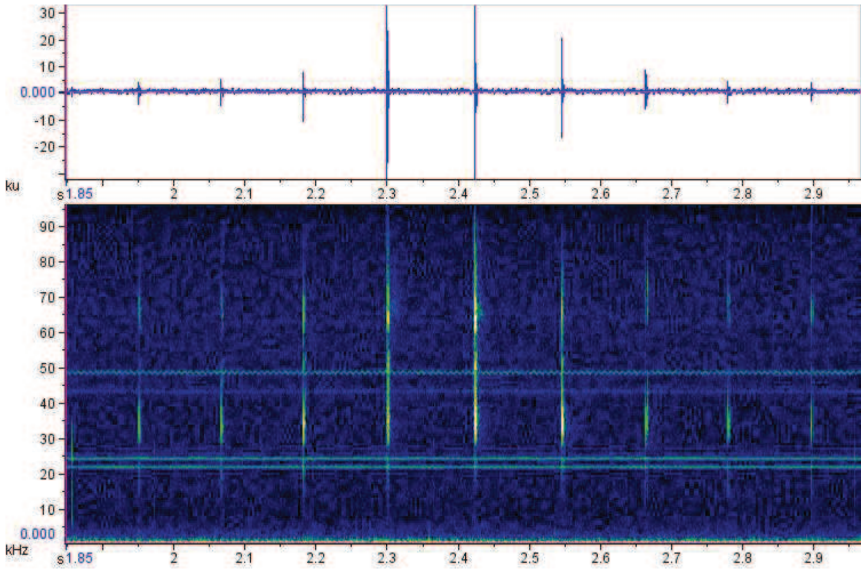


Figure 11: Example of waveform (top panel) and spectrogram (bottom panel) of a series of clicks from an individual Sowerby's beaked whale.
(FFT: 512 pts, 50% overlap, Hann window)

Detected clicks were manually assigned to series of click trains (fig. 12) based on simultaneous comparison of spectrograms of the acoustic data and the bearing patterns as determined by Pamguard. Target-motion analysis was conducted for thirteen click trains, resulting in two-dimensional localizations for animals ranging from 82 – 456 m from the trackline. Based on relative locations, these click trains appeared to be produced by 3 – 5 individuals.

Click train series from three individuals were chosen for application of 3-D analysis (tab. 2). These individuals were estimated to be at radial distances of 192-250 m from the array. Click waveforms were visually evaluated to confirm the presence of multipath arrivals. For each click train, the time difference of arrival for direct and surface-reflected signals was compared for up to 5 different clicks and across three channels. The 2-D localization results from Pamguard were used as range inputs. Three-dimensional localization for these three individuals revealed vocalization depths ranging from 6 – 36 m.

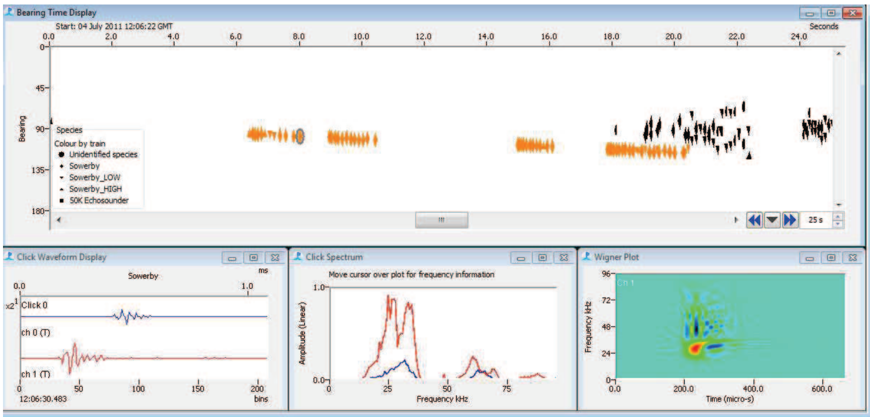


Figure 12: Top: Bearing-time display in Pamguard. Detected clicks are indicated by triangles. Orange triangles indicate clicks that were manually assigned to one click train series; black triangles represent clicks that are unassigned to individuals. Bottom (from left to right): The waveform display of one selected click (indicated by the gray circle in the top panel), the frequency spectrum, and Wigner plot.

Table 2: Data for three series of click trains representing three animals. Clicks were manually assigned to series based on simultaneous spectrogram and bearing-time review. Radial distances were approximations obtained from two-dimensional localization in Pamguard. Source depths were averaged over a series of clicks from multiple channels. Array depth was 12 m, ocean bottom depth was approximately 1000 m in area of encounter.

Individual	# Clicks Assigned to Click Train	Mean time difference (ms) between direct & reflected arrivals	Radial Distance (m)	Mean Depth (m)
1	57	0.44	192	**5.9 ±1.3**
2	88	0.9	247	**13.7 ±9.7**
3	96	2.31	250	**35.8 ±1.3**

The depths of the three individuals that were localized in 3-D are substantially less than those obtained from tagged individuals of both Cuvier's and Blainville's beaked whales, suggesting that the vocal behavior of Sowerby's beaked whales may differ from other ziphiids. The difference between the slant distance and the perpendicular distance estimated by traditional methods is minor for these individuals, given the shallow depths at which they were vocalizing. However, broader application of this methodology across multiple encounters is needed to characterize the average depths at which this species is detected. Further investigations may reveal whether the differences in depths at which different species vocalize are context-driven or species-specific.

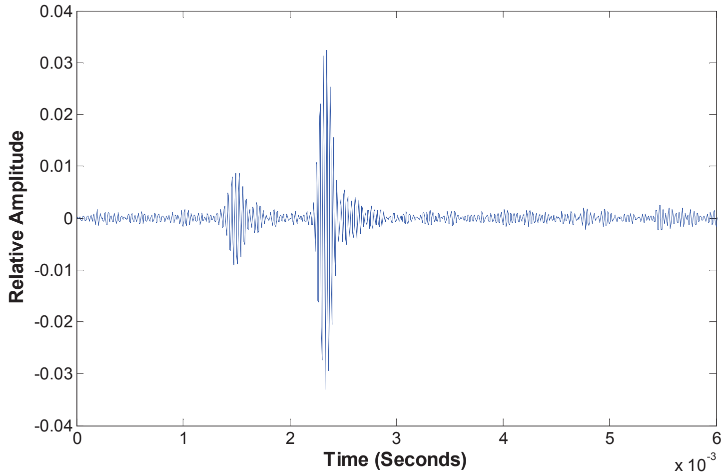


Figure 13: An example of beam focusing taken from an echolocation click recorded during the encounter with Sowerby's beaked whales. Note that the second arrival is of higher amplitude than the direct path.

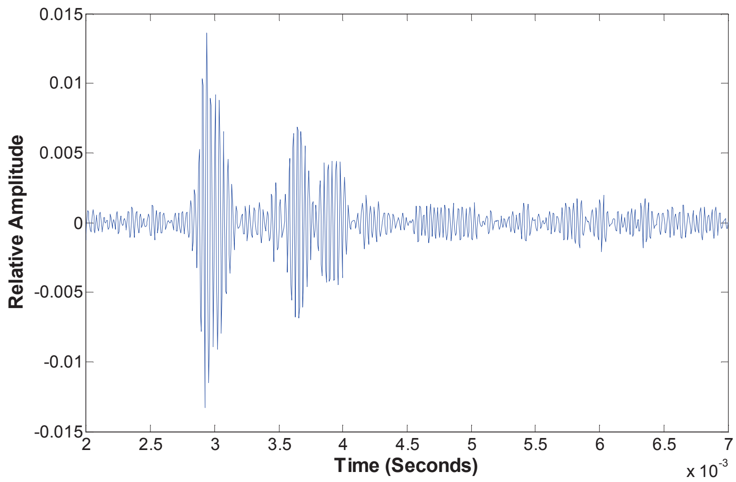


Figure 14: An example of a direct signal followed by a double surface reflection, recorded during the encounter with Sowerby's beaked whales.

Application of three-dimensional localization methods to high-frequency signals such as these is complicated by the effects of sea surface conditions. Depending on the sea state, when the wavelength of the signal is short compared to that of waves on the sea surface, propagation effects such as beam focusing or multiple reflections may occur adding difficulty to resolving time difference of arrival. These effects were observed in our towed array data, as well in similar experiments focusing on signal processing (Preisig and Deane 2004). In the case of beam focusing, (fig. 13) the received reflection will appear to have a greater amplitude than the direct signal. This is caused by the concave shape of a surface wave creating an acoustic focal point for reflections near the array. Multiple surface reflections (fig. 14) result in two or more first order reflections and can cause confusion when attempting to resolve the correct time difference of arrival required for bearing estimation. Additionally, because the recordings are being made in a dynamic environment, these effects will change continuously over time adding additional complication. It is assumed that these effects will have a greater significance at shallow depths, however additional work must be done to verify this and to resolve what the true time difference of arrival should be in the case of a perfectly flat sea surface.

4. Discussion

Passive acoustic monitoring (PAM) is a rapidly growing field in marine ecological research. For many species, these new PAM applications and the ensuing increase in temporal and spatial monitoring coverage have resulted in new knowledge on seasonal and regional distribution patterns (e.g., Lammers *et al*., 2011; McDonald *et al*., 2009; Mussoline *et al*., 2012; Simon *et al*., 2010). In addition, analyses of acoustic data have allowed us to gain new insights into species-specific behaviors (Baumgartner and Fratantoni, 2008; Jensen *et al*., 2011), as well as to elucidate behavioral changes due to acoustic disturbance (Holt *et al*., 2009; Melcon *et al*., 2012; Parks *et al*., 2011a; Risch *et al*., 2012).

One main aspect of measuring the effects of disturbance is to asses changes in the distribution and density of species or populations inhabiting the impacted area. For species of high risk and low densities, such as the Baltic harbor porpoise or the North Pacific right whale (Kyhn *et al*., 2012; Marques *et al*., 2011), this is especially important. Since visual density estimation is difficult in these cases, acoustics might be particularly useful to augment traditional methods of assessing changes in abundance.

For successful density estimation from acoustic data, it is essential to obtain cue rates in different behavioral contexts and as a function of time, season, region and life-history parameters such as age and sex (see Marques *et al*., 2012). PAM can be used to localize and track vocal animals. Thus, some of these parameters, such as minimum group sizes, calling rates, as well as source level and detectability under different background noise scenarios can be estimated using these data.

The two case studies presented in the current chapter were selected to highlight the feasibility of using data from bottom-mounted recording units and towed hydrophone arrays to estimate some of these parameters. The 2-D localization of right whale up-calls and the tracking of several individuals in the first case study demonstrated the relative ease with which passive acoustic analyses can be used to estimate minimum group size and individual calling rates. Despite applying it to only one hour of data, call rates and bout lengths found in this analysis were similar to previously published data collected from archival recording tags (Parks *et al*., 2011b). This demonstrates that bottom-mounted recorder data, when synchronized into a time-aligned array, can be used to supplement other data collection methodologies on a broader scale.

Species-specific automatic detectors (e.g., ISRAT (Urazghildiiev and Clark, 2006)) and semi-automated localization algorithms can be applied to quickly access large quantities of data, facilitating analyses of datasets covering spatial and temporal scales important for conservation and management. The biggest advantage of large data sets, like those provided by long-term PAM is the ability to address questions of high variability in behavior as found in smaller, more controlled studies (Parks *et al*., 2011b). To date, few studies (e.g., Parks *et al*., 2012; Širović *et al*., 2004) have used passive acoustic data and localization techniques to estimate calling rates and minimum group size of baleen whales on a larger scale. In addition, PAM data can provide source level estimates for individual animals (Munger *et al*., 2011; Samaran *et al*., 2010; Stafford *et al*., 2007; Širović *et al*., 2007). If coupled with acoustic propagation models, robust source level information can then be applied to estimate detection ranges of species-specific calls.
Currently, more studies have used 2-D localization approaches as part of towed array surveys (Barlow and Taylor, 2005a; Lewis *et al*., 2007; Li *et al*., 2009). In our second case study, we utilized the freely available software package Pamguard (Gillespie *et al*., 2008) to detect and track beaked whale clicks from towed array data. In the context of towed array recordings, the estimation of distance to the survey trackline, species

identification and minimum number of animals by passive acoustic tracking can improve simultaneously collected visual data by providing context to the visual encounter, aiding in species identification, as well as augmenting traditional density estimates. In the current example, the simultaneous collection of visual and acoustic data allowed for the description of the previously unknown acoustic signature of an understudied species (Cholewiak *et al*., submitted).

Estimating the depth ranges at which marine mammals are vocalizing can provide important behavioral information and help interpret PAM datasets. Although in theory the standard method of localization using 'Time Difference of Arrival' (TDOA) is capable of localizing animals in three dimensions, in practicality, for fixed arrays, this method is generally suitable for only two-dimensional or planar applications. If recorders are separated by several kilometers or more, then the change in absolute path length (the length as a function of both depths an horizontal distance) is negligible with a change in calling depth unless the difference in depth between the vocalizing animal and recorder is very large. For applications where the animal's depth is small compared to path length, the resulting changes in time difference of arrival between recorders as a function of depth will likely be beyond the resolution achievable when considering limits such as sampling rate and synchronization error. Limitations to depth estimations and three dimensional localization with fixed arrays can be overcome through the application of the Direct-Reflected Time Difference of Arrival (DRTD), as demonstrated for localizing right whales in the first case study. Only a few studies have used PAM data for 3-D localization of vocalizing animals (Newhall *et al*., 2012; Wiggins *et al*., 2004). However, with the application of methods such as the DRTD (Aubauer *et al*., 2000; Mouy *et al*., 2012; Nosal and Frazer, 2006; Valtierra *et al*., submitted), PAM data can be used to augment and significantly increase the availability of data on baleen whale calling depths, which have so far been collected mainly from tagged animals (Oleson *et al*., 2007b; Parks *et al*., 2011b).

Three-dimensional localization techniques have more frequently been conducted using odontocete signals (e.g., Giraudet and Glotin, 2006; Thode, 2005). Incorporating these techniques into towed array surveys has been done with sperm whales (Barlow and Taylor, 2005), but has not been applied to other species. For some deep-diving species such as beaked whales, much of what we know of their underwater behavior comes from tagging studies of few species in limited contexts. Case study 2 shows how the DRTD method of 3-D localization can be combined with 2-D localization of towed array data to obtain depth of vocalizing animals. This may have implications for improving distance estimation, which will ultimately result in an improved detection function for density estimation.

Obtaining depth estimates for calling individuals is important for improving our knowledge of basic calling behavior and the implications of such on density estimation, as well as in a context of management and mitigation. Under certain sound speed profile conditions, modeling the range over which calls propagate may be heavily dependent on the animal's location within the water column (Stafford *et al*., 2007; Thode, 2005). Moreover animals might be actively choosing a certain calling depth in order to increase signal strength of their calls (Oleson *et al*., 2007b). Thus, knowledge on preferred depths for vocalizing animals is crucial in order to estimate detection probability of species-specific calls from PAM data. In addition, the received levels of directional sound sources such as seismic arrays may be much greater for animals at depth than at the surface (Thode, 2005). In addition, animals that spend significant amounts of time in shallow depths will be more vulnerable to ship-strike (Parks *et al*., 2012b). In the case of vocalizing animals, PAM data can elucidate these behavioral patterns and supplement data which have traditionally been obtained with short-term recording tags (Jensen *et al*., 2011; Oleson *et al*., 2007b; Parks *et al*., 2011b).

In recent years, there has been a surge in the development of offshore industries, including oil and gas, as well as emerging alternative energy projects such as tidal turbines, wave energy or windfarms (Simmonds and Brown, 2010). In this context, successful species management and conservation is dependent upon accurate knowledge of temporal and spatial distribution patterns and population densities of a given species. As a result we have seen an increased effort, both spatially and temporally, of using PAM for monitoring and mitigation. Examples are large-scale projects such as for monitoring ocean noise in the Stellwagen Bank National Marine Sanctuary (Hatch *et al*., 2012), extensive acoustic monitoring in the Arctic ocean for mitigating seismic exploration (Moore *et al*., 2012), or the SAMBAH project (http://www.sambah.org/) to assess harbor porpoise density in the Baltic Sea.

In this chapter, we highlighted how combining PAM data with two- and three-dimensional localization and tracking techniques can be used to expand baseline vocalization data, extracting critical information such as animal depth and calling rate. Expanded application of these tools to fixed and towed array data will enable more detailed analyses of the inherent variability in species-specific calling behaviors. This knowledge in turn will facilitate the direct application of acoustic data to abundance estimation, ultimately improving marine mammal management.

Authors' affiliations

Danielle CHOLEWIAK[31], Denise RISCH[1], Robert VALTIERRA[2], and Sofie M. VAN PARIJS[1]

[1] Protected Species Branch, NOAA Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543
[2] Boston University, Department of Mechanical Engineering, 110 Cummington Street, Boston, MA 02215

Acknowledgements

The authors would like to thank our friends and colleagues at the Stellwagen Bank National Marine Sanctuary, the crew of the R/V Auk, and the Bioacoustics Research Program, Cornell Laboratory of Ornithology, for their support conducting the research in SBNMS. For the towed hydrophone array work, the authors would like to thank Debra Palka, the crew of the R/V Bigelow and the scientists who participated in the AMAPPS 2011 survey. We thank R. Glynn Holt for supporting the development of the localization work. We also thank colleagues at the Northeast Fisheries Science Center Protected Species Branch for their assistance and support throughout these projects. Funding was provided by the U.S. Navy N45 Program, the Bureau of Ocean Energy Management within the Atlantic Marine Assessment Program for Protected Species, the NOAA Ocean Acoustics Program and an ONR (grant # N00014-07-1-1029) awarded by the National Oceanographic Partnership Program. One of the authors (R.V.) was also supported by an NSF GK-12 fellowship and an ASA Minority Fellowship.

References

Aubauer, R., Lammers, M. O., and Au, W. W. L. (2000). "One-hydrophone method of estimating distance and depth of phonating dolphins in shallow water," The Journal of the Acoustical Society of America 107, 2744–2749.

Baird, R. W., Webster, D. L., McSweeney, D. J., Ligon, A. D., Schorr, G. S., and Barlow, J. (2006). "Diving behaviour of Cuvier's (*Ziphius cavirostris*) and Blainville's (*Mesoplodon densirostris*) beaked whales in Hawai'i," Canadian Journal of Zoology 84, 1120–1128.

Barlow, J. (1999). "Trackline detection probability for long-diving whales," In G. W. Garner, S. C. Amstrup, J. L. Laake, B. F. J. Manly, L. L. McDonald, and D. G. Robertson (Eds.), Marine Mammal Survey and Assessment Methods(A.A. Balkema, Rotterdam), pp. 209–221.

[*] First and second authors contributed equally to this chapter.

Barlow, J., Ferguson, M. C., Perrin, W. F., Ballance, L., Gerrodette, T., Joyce, G. G., MacLeod, C. D., *et al*. (2006). “Abundance and densities of beaked and bottlenose whales (family *Ziphiidae*),” Journal of Cetacean Research and Management 7, 263–270.

Barlow, J., and Taylor, B. L. (2005). “Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey,” Marine Mammal Science 21, 429–445.

Baumann-Pickering, S., Simonis, A. E., Wiggins, S. M., Brownell, R. L., and Hildebrand, J. a. (2012). “Aleutian Islands beaked whale echolocation signals,” Marine Mammal Science, doi: 10.1111/j.1748-7692.2011.00550.x.

Baumann-Pickering, S., Wiggins, S. M., Roth, E. H., Roch, M. A., Schnitzler, H.-U., and Hildebrand, J. A. (2010). “Echolocation signals of a beaked whale at Palmyra Atoll,” The Journal of the Acoustical Society of America 127, 3790–3799.

Baumgartner, M. F., and Fratantoni, D. M. (2008). “Diel periodicity in both sei whale vocalization rates and the vertical migration of their copepod prey observed from ocean gliders,” Limnology and Oceanography 53, 2197–2209.

Borchers, D., Marques, T., Gunnlaugsson, T., and Jupp, P. (2010). “Estimating Distance Sampling Detection Functions When Distances Are Measured With Errors,” Journal of Agricultural, Biological, and Environmental Statistics 15, 346–361.

Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D. L., and Thomas, L. (2001). Introduction to Distance Sampling - Estimating Abundances of Biological Populations (Oxford University Press, Oxford).

Caldwell, M. C., and Caldwell, D. K. (1991). A Note Describing Sounds Recorded from Two Cetacean Species, *Kogia breviceps* and *Mesoplodon europaeus*, Stranded in Northeastern Florida NOAA TECHNICAL REPORTS National Marine Fisheries ServiceVol. 98, pp. 151–154.

Calupca, T., Fristrup, K. M., and Clark, C. (2000). “A compact digital recording system for autonomous bioacoustic monitoring,” Journal of the Acoustical Society of America 108, 2582.

Charif, R. A., Clark, C. W., and Fristrup, K. M. (2004). “Raven 12 User’s Manual,”.

Clark, C. W., Brown, M. W., and Corkeron, P. (2010). “Visual and acoustic surveys for North Atlantic right whales, *Eubalaena glacialis*, in Cape Cod Bay, Massachusetts, 2001-2005: Management implications,” Marine Mammal Science 26, 837–854.

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L. T., Van Parijs, S.

M., Frankel, A. S., and Ponirakis, D. (2009). "Acoustic masking in marine ecosystems: intuitions, analysis, and implication," Marine Ecology Progress Series 395, 201–222.

Cortopassi, K. A., and Fristrup, K. M. (2005). "A robust method for localization of animal sounds," 2nd International Workshop on Detection and Loc. of Marine Mammals using Passive Acoustics.

Davidson, A. D., Boyer, A. G., Kim, H., Pompa-Mansilla, S., Hamilton, M. J., Costa, D. P., Ceballos, G., *et al*. (2012). "Drivers and hotspots of extinction risk in marine mammals," Proceedings of the National Academy of Sciences of the United States of America 109, 3395–400.

Dawson, S., and Ljungblad, D. (1998). "Sounds recorded from baird' s beaked whale, *Berardius Bairdii*," Marine Mammal Science 14, 335–344.

Figueroa, H. K., and Robbins, M. (2008). "XBAT: An open-source extensible platform for bioacoustic research and monitoring," In K.-H. Frommolt, R. Bardeli, and M. Clausen (Eds.), Computational bioacoustics for assessing biodiversity (Bundesamt für Naturschutz, Bonn), pp. 143–155.

Fujiwara, M., and Caswell, H. (2001). "Demography of the endangered North Atlantic right whale," Nature 414, 537–541.

Gillespie, D. (1997). "An acoustic survey for sperm whales in the southern ocean sanctuary conducted from RSV Aurora Australis," Reports of the International Whaling Commission 47, 897–906.

Gillespie, D., Dunn, C., Gordon, J., Claridge, D., Embling, C., and Boyd, I. (2009). "Field recordings of Gervais' beaked whales *Mesoplodon europaeus* from the Bahamas," The Journal of the Acoustical Society of America 125, 3428–33.

Gillespie, D., Gordon, J., Mchugh, R., Mclaren, D., Mellinger, D. K., Redmond, P., Thode, A., *et al*. (2008). "PAMGUARD: Semiautomated, open source software for real-time acoustic detection and localisation of cetaceans," Proceedings of the Institute of Acoustics.

Giraudet, P., and Glotin, H. (2006). "Real-time 3D tracking of whales by echo-robust precise TDOA estimates with a widely-spaced hydrophone array," Applied Acoustics 67, 1106–1117.

Halpern, B. S., Selkoe, K. A., Micheli, F., and Kappel, C. V (2007). "Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats," Conservation Biology 21, 1301–15.

Hatch, L. T., Clark, C. W., VAN Parijs, S. M., Frankel, A. S., and Ponirakis, D. W. (2012). "Quantifying loss of acoustic Communication space for right whales in and around a US National Marine Sanctuary," Conservation Biology 26, 983–994.

Hen, I., Sakov, A., Kafkafi, N., Golani, I., and Benjamini, Y. (2004). "The dynamics of spatial behavior: how can robust smoothing techniques help?," Journal of Neuroscience Methods 133, 161–172.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., and Veirs, S. (2009). "Speaking up: Killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise," JASA Express Letters 125, EL27–EL32.

Hooker, S. K., and Whitehead, H. (2002). "Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*)," Marine Mammal Science 18, 69–80.

Jensen, F. H., Perez, J. M., Johnson, M., Soto, N. A., and Madsen, P. T. (2011). "Calling under pressure: short-finned pilot whales make social calls during deep foraging dives," Proceedings of the Royal Society B: Biological Sciences 278, 3017–3025.

Johnson, M. P., Madsen, P. T., Zimmer, W. M. X., Aguilar De Soto, N., and Tyack, P. L. (2004). "Beaked whales echolocate on prey," Biology Letters, doi: 10.1098/rsbl.2004.0208.

Johnson, M. P., and Tyack, P. L. (2003). "A digital acoustic recording tag for measuring the response of wild marine mammals to sound," IEEE Journal of Oceanic Engineering 28, 3–12.

Kappel, C. V (2005). "Losing pieces of the puzzle: Threats to marine, estuarine and diadromous species," Frontiers in Ecology and the Environment 3, 275–282.

Kraus, S. D. (1990). "Rates and potential causes of mortality in North Atlantic righ whales (*Eubalaena glacialis*)," Marine Mammal Science 6, 278–291.

Kraus, S. D., Brown, M. W., Caswell, H., Clark, C. W., Fujiwara, M., Hamilton, P. K., Kenney, R. D., *et al*. (2005). "North Atlantic right whales in crisis," Science 309, 561–562.

Küsel, E. T., Mellinger, D. K., Thomas, L., Marques, T. a, Moretti, D., and Ward, J. (2011). "Cetacean population density estimation from single fixed sensors using passive acoustics," The Journal of the Acoustical Society of America 129, 3610–22.

Küsel, E. T., Mellinger, D. K., Thomas, L., Marques, T. A., Moretti, D. J., and Ward, J. (2009). "Estimating beaked whale density from single hydrophones by means of propagation modeling", J. Acoust. Soc. Am., vol 125(4), pp. 2589-2589.

Kyhn, L. A., Tougaard, J., Thomas, L., Duve, L. R., Stenback, J., Amundin, M., Desportes, G., *et al*. (2012). "From echolocation clicks to animal density—Acoustic sampling of harbor porpoises with static dataloggers," The Journal of the Acoustical Society of America 131, 550–560.

Lammers, M. O., Fisher-Pool, P. I., Au, W. W. L., Meyer, C. G., Wong, K. B., and Brainard, R. E. (2011). "Humpback whale *Megaptera novaeangliae* song reveals wintering activity in the Northwestern Hawaiian Islands," Marine Ecology Progress Series 423, 261–268.

Lewis, T., Gillespie, D., Lacey, C., Matthews, J., Danbolt, M., Leaper, R., McLanaghan, R., *et al*. (2007). "Sperm whale abundance estimates from acoustic surveys of the Ionian Sea and Straits of Sicily in 2003," Journal of the Marine Biological Association of the UK 87, 353.

Li, S., Akamatsu, T., Wang, D., and Wang, K. (2009). "Localization and tracking of phonating finless porpoises using towed stereo acoustic data-loggers," The Journal of the Acoustical Society of America 126, 468–75.

Lynn, S. K., and Reiss, D. (1992). "Pulse sequence and whistle production by two captive beaked whales, *Mesoplodon* species," Marine Mammal Science, 8, 299–305.

Marques, T. a, Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. a, Moretti, D. J., Harris, D., *et al*. (2012). "Estimating animal population density using passive acoustics," Biological reviews of the Cambridge Philosophical Society, doi: 10.1111/brv.12001.

Marques, T. A., Munger, L., Thomas, L., Wiggins, S., and Hildebrand, J. A. (2011). "Estimating North Pacific right whale *Eubalaena japonica* density using passive acoustic cue counting," Endangered Species Research 13, 163–172.

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Jarvis, S., Morrissey, R. P., Ciminello, C.-A., *et al*. (2010). "Spatially explicit capture–recapture methods to estimate minke whale density from data collected at bottom-mounted hydrophones," Journal of Ornithology, doi: 10.1007/s10336-010-0535-7.

Marques, T. A., Ward, J., Thomas, L., DiMarzio, N., Tyack, P. L., Moretti, D., and Martin, S. (2009). "Estimating Blainville's beaked whale density at AUTEC using passive acoustic data,".

Marten, K. (2000). "Ultrasonic analysis of pygmy sperm whale (Kogia breviceps) and Hubbs' beaked whale (*Mesoplodon carlhubbsi*) clicks," Aquatic Mammals 26, 45–48.

Martin, S. W., Marques, T. a., Thomas, L., Morrissey, R. P., Jarvis, S., DiMarzio, N., Moretti, D., *et al*. (2012). "Estimating minke whale (*Balaenoptera acutorostrata*) boing sound density using passive acoustic sensors," Marine Mammal Science, doi: 10.1111/j.1748-7692.2011.00561.x.

Matthews, J. N., Brown, S., Gillespie, D., Johnson, M. P., McLanaghan, R., Moscrop, A., Nowacek, D. P., *et al*. (2001). "Vocalisation rates of the North Atlantic right whale (*Eubalaena glacialis*)," Journal of

Cetacean Research and Management 3, 271–282.
McDonald, M. A., and Fox, C. G. (1999). "Passive acoustic methods applied to fin whale population density estimation," The Journal of the Acoustical Society of America 105, 2643–2651.
McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., Johnston, D. W., and Polovina, J. J. (2009). "An acoustic survey of beaked whales at Cross Seamount near Hawaii," The Journal of the Acoustical Society of America 125, 624–7.
Melcon, M. L., Failla, M., and Iniguez, M. A. (2012). "Echolocation behavior of franciscana dolphins (*Pontoporia blainvillei*) in the wild," JASA Express Letters 131, 448–453.
Melcón, M. L., Cummins, A. J., Kerosky, S. M., Roche, L. K., Wiggins, S. M., and Hildebrand, J. A. (2012). "Blue whales respond to anthropogenic noise," PLoS ONE 7, e32681.
Mellinger, D. K. (2004). "A comparison of methods for detecting right whale calls," Canadian Acoustics 32, 55–65.
Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S., and Clark, C. W. (2012). "A New Framework for Assessing the Effects of Anthropogenic Sound on Marine Mammals in a Rapidly Changing Arctic," BioScience 62, 289–295.
Morano, J. L., Rice, A. N., Tielens, J. T., Estabrook, B. J., Murray, A., Roberts, B. L., and Clark, C. W. (2012). "Acoustically Detected Year-Round Presence of Right Whales in an Urbanized Migration Corridor," Conservation Biology, doi: 10.1111/j.1523-1739.2012.01866.x.
Moretti, D., Marques, T. A., Thomas, L., DiMarzio, N., Dilley, A., Morrissey, R., McCarthy, E., *et al*. (2010). "A dive counting density estimation method for Blainville's beaked whale (*Mesoplodon densirostris*) using a bottom-mounted hydrophone field as applied to a Mid-Frequency Active (MFA) sonar operation," Applied Acoustics 71, 1036–1042.
Mouy, X., Hannay, D., Zykov, M., and Martin, B. (2012). "Tracking of Pacific walruses in the Chukchi Sea using a single hydrophone," The Journal of the Acoustical Society of America 131, 1349–1358.
Munger, L. M., Wiggins, S. M., and Hildebrand, J. a (2011). "North Pacific right whale up-call source levels and propagation distance on the southeastern Bering Sea shelf," The Journal of the Acoustical Society of America 129, 4047–54.
Mussoline, S. E., Risch, D., Hatch, L. T., Weinrich, M. T., Wiley, D. N., Thompson, M. A., Corkeron, P. J., *et al*. (2012). "Seasonal and diel variation in North Atlantic right whale up-calls: implications for management and conservation in the northwestern Atlantic Ocean," Endangered Species Research 17, 17–26.

Newhall, A. E., Lin, Y., Lynch, J. F., Hole, W., Baumgartner, M. F., and Gawarkiewicz, G. G. (2012). "Long distance passive localization of vocalizing sei whales using an acoustic normal mode approach," Journal of the Acoustical Society of America 131, 1814–1825.

Nosal, E., and Frazer, L. N. (2006). "Track of a sperm whale from delays between direct and surface-reflected clicks," Applied Acoustics 67, 1187–1201.

Oleson, E. M., Calambokidis, J., Barlow, J., and Hildebrand, J. A. (2007). "Blue whale visual and acoustic encounter rates in the Southern California Bight," Marine Mammal Science 23, 574–597.

Oleson, E. M., Calambokidis, J., Burgess, W. C., Mcdonald, M. A., LeDuc, C. A., and Hildebrand, J. A. (2007). "Behavioral context of call production by eastern North Pacific blue whales," Marine Ecology Progress Series 330, 269–284.

Parks, S. E., Hamilton, P. K., Kraus, S. D., and Tyack, P. L. (2005). "The gunshot sound produced by male North Atlantic right whales (*Eubalaena glacialis*) and its potential function in reproductive advertisement," Marine Mammal Science 21, 458–475.

Parks, S. E., Hotchkin, C. F., Cortopassi, K. A., and Clark, C. W. (2012). "Characteristics of gunshot sound displays by North Atlantic right whales in the Bay of Fundy," The Journal of the Acoustical Society of America 131, 3173–3179.

Parks, S. E., Johnson, M., Nowacek, D., and Tyack, P. L. (2011). "Individual right whales call louder in increased environmental noise," Biology Letters 7, 33–35.

Parks, S. E., Searby, A., Célérier, A., Johnson, M. P., Nowacek, D. P., and Tyack, P. L. (2011). "Sound production behavior of individual North Atlantic right whales: implications for passive acoustic monitoring," Endangered Species Research 15, 63–76.

Parks, S. E., and Tyack, P. L. (2005). "Sound production by North Atlantic right whales (*Eubalaena glacialis*) in surface active groups," The Journal of the Acoustical Society of America 117, 3297–3306.

Parks, S. E., Warren, J. D., Stamieszkin, K., Mayo, C. a, and Wiley, D. (2012). "Dangerous dining: surface foraging of North Atlantic right whales increases risk of vessel collisions," Biology letters 8, 57–60.

Pendleton, D. E., Sullivan, P. J., Brown, M. W., Cole, T. V. N., Good, C. P., Mayo, C. A., Monger, B. C., *et al*. (2012). "Weekly predictions of North Atlantic right whale Eubalaena glacialis habitat reveal influence of prey abundance and seasonality of habitat preferences," Endangered Species Research 18, 147–161.

Rankin, S., and Barlow, J. (2007). "Sounds recorded in the presence of Blainville's beaked whales, *Mesoplodon densirostris*, near Hawai'i," The Journal of the Acoustical Society of America 122, 42–5.

Rankin, S., Baumann-Pickering, S., Yack, T., and Barlow, J. (2011). "Description of sounds recorded from Longman's beaked whale, *Indopacetus pacificus*," The Journal of the Acoustical Society of America 130, EL339–44.

Read, A. J. (2008). "The Looming Crisis: Interactions between marine mammals and fisheries," Journal of Mammalogy 89, 541–548.

Risch, D., Corkeron, P. J., Ellison, W. T., and Van Parijs, S. M. (2012). "Changes in Humpback Whale Song Occurrence in Response to an Acoustic Source 200 km Away," (H. Browman, Ed.)PLoS ONE 7, e29741.

Samaran, F., Guinet, C., Adam, O., Motsch, J.-F., and Cansi, Y. (2010). "Source level estimation of two blue whale subspecies in southwestern Indian Ocean," The Journal of the Acoustical Society of America 127, 3800–8.

Simmonds, M. P., and Brown, V. C. (2010). "Is there a conflict between cetacean conservation and marine renewable-energy developments?," Wildlife Research 37, 688.

Simon, M., Stafford, K. M., Beedholm, K., Lee, C. M., and Madsen, P. T. (2010). "Singing behavior of fin whales in the Davis Strait with implications for mating, migration and foraging," The Journal of the Acoustical Society of America 128, 3200–10.

Širović, A., Hildebrand, J. A., and Wiggins, S. M. (2007). "Blue and fin whale call source levels and propagation range in the Southern Ocean," The Journal of the Acoustical Society of America 122, 1208–1215.

Širović, A., Hildebrand, J. A., Wiggins, S. M., McDonald, M. A., Moore, S. E., and Thiele, D. (2004). "Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula," Deep Sea Research Part II: Topical Studies in Oceanography 51, 2327–2344.

Slater, P., and Lester, N. (1981). "Minimising errors in splitting behaviour into bouts," Behaviour 79, 153–161.

Stafford, K. M., Mellinger, D. K., Moore, S. E., and Fox, C. G. (2007). "Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999-2002," The Journal of the Acoustical Society of America 122, 3378–3390.

Thode, A. (2005). "Three-dimensional passive acoustic tracking of sperm whales (*Physeter macrocephalus*) in ray-refracting environments," The Journal of the Acoustical Society of America 118, 3575–3584.

Tyack, P. L., Johnson, M., Soto, N. A., Sturlese, A., and Madsen, P. T. (2006). "Extreme diving of beaked whales," The Journal of Experimental Biology 209, 4238–4253.

Urazghildiiev, I. R., and Clark, C. W. (2006). "Acoustic detection of

North Atlantic right whale contact calls using the generalized likelihood ratio test," J. of the Acoust. Soc. of Am., 120, 1956–1963.

Vaage, S., and Ursin, B. (1987). "Computation of signatures of linear airgun arrays," Geophysical Prospecting 35, 281–287.

Valtierra, R. D., Holt, R. G., Cholewiak, D. M., and Van Parijs. S. M., (2013, in press). "Calling depths of baleen whales from single sensor data: Development of an autocorrelation method using multipath localization," The Journal of the Acoustical Society of America.

Van Parijs, S. M., Clark, C. W., Sousa-lima, R. S., Parks, S. E., Rankin, S., Risch, D., and Van Opzeeland, I. C. (2009). "Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales," Marine Ecology Progress Series 395, 21–36.

Vanderlaan, A. S. M., Hay, A. E., and Taggart, C. T. (2003). "Characterization of North Atlantic right-whale (*Eubalaena glacialis*) sounds in the Bay of Fundy," IEEE Journal of Ocean Eng. 28 164–173.

Vu, E. T., Risch, D., Clark, C. W., Gaylord, S., Hatch, L. T., Thompson, M. A., Wiley, D. N., *et al*. (2012). "Humpback whale song occurs extensively on feeding grounds in the western North Atlantic Ocean," Aquatic Biology 14, 175–183.

Waring, G. T., Josephson, E., Fairfield, C. P., and Maze-Foley, K. (2009). US Atlantic and Gulf of Mexico Marine Mammal Stock Assessments 2008 pp. 1–429.

Wiggins, S. M., McDonald, M. A., Munger, L. M., Moore, S. E., and Hildebrand, J. A. (2004). "Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea," Canadian Acoustics 32, 146–154.

Wiley, D., Ware, C., Bocconcelli, A., Cholewiak, D., Friedlaender, A., Thompson, M., and Weinrich, M. (2011). "Underwater components of humpback whale bubble-net feeding behaviour," Behaviour 148, 575–602.

Yack, T. M., Barlow, J., Calambokidis, J., Ballance, L. T., Pittman, R., and McKenna, M. F. (2011). "Passive Acoustic Beaked Whale Monitoring Survey of the Channel Islands, California," NOAA Technical Memorandum NMFS.

Zimmer, W. M. X., Harwood, J., Tyack, P. L., Johnson, M. P., and Madsen, P. T. (2008). "Passive acoustic detection of deep-diving beaked whales," The Journal of the Acoustical Society of America 124, 2823–32.

Zimmer, W. M. X., Johnson, M. P., Madsen, P. T., and Tyack, P. L. (2005). "Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*)," J. of the Acoust Soc of Am., 117, 3919–3927.